A

THE DEVELOPMENT

OF THE

PHILOSOPHY

OF THE

STEAM-ENGINE.

An Historical Sketch

BY

ROBERT H. THURSTON.

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INTRODUCTION.

The following sketch of the development of the philosophy of the modern steam-engine, and of the various heat-engines embodying the same principles, was originally prepared by the Author in the year 1883–4, and was presented to the British Association for Advancement of Science, when holding their session of 1884 on this side the Atlantic, at Montreal. The paper was given a very favorable place, and was later selected for incorporation, in full, in the transactions of that year. It has now been revised, and with slight modifications, and with the additional matter of the last page or two, is now reprinted for more general circulation. The present seems a very appropriate time for the publication of this sketch in a more permanent and more accessible form. It cannot be said that the theory of the steam-engine is yet in its final and complete, its most perfect and most

practically available, form. Its final shape must probably be given it by some such master of mathematical and physical science as was Rankine, or such as was Clausius; but the main principles and the essential facts of a complete theory are unquestionably now well determined and well recognized by the most advanced thinkers and most intelligent practitioners, and are in various ways presented by the recognized authorities among later writers. It is at least practicable, to-day, whenever a design is to be prepared, to compute from known and well-established data the probable wastes of the engine and its efficiency under prescribed conditions, and with such accuracy that no serious apprehension need be felt by the designing engineer in regard to the ultimate outcome of his venture financially and commercially. It is always the commercial aspect of the case that most concerns him. The method of Professor Marks may be adopted in computing the heat-transfer and consequent waste within the engine, for all cases of similar character to those for which the data were taken by him, and probably for a much wider range of conditions.*

* Relative Proportions of the Steam-engine; Phil. 1888.

The method of computation of efficiency of engine and of fuel and steam consumption adopted by Mr. Buel is another illustration of a complete and practical system of treating familiar cases when, as in those taken by him, the data may be assumed fairly well established for such engine.* The Author has elsewhere shown how the several efficiencies of the engine, including the commercial problems, may be treated to secure practically available results, and it is thus evident that the engineer has to-day all the elements previously lacking of a valuable and satisfactory system of engine designing.†

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* American Machinist, 1888.

† The Several Efficiencies of the Steam-engine, Trans. Am. Soc. M. E., 1882; Jour. Frank. Inst., 1882.

DEVELOPMENT OF THE THEORY OF THE STEAM-ENGINE AND ITS APPLICATIONS.*

A COMPLETE history of the development of the Theory of the Steam-engine would include, first, the history of the Mechanical Theory of Heat; secondly, the history of the Science of Thermodynamics, which has been the outgrowth of that theory; third, the history of the application of the science of heat-transformation to the case of the Steam-engine; and, fourthly, an account of the completion of the Theory of the Steam and other Heat Engines by the introduction of the theory of losses by the more or less avoidable forms of waste, as distinguished from those necessary and unavoidable wastes indicated by the pure theory of

* Read, with slight modifications, at the Montreal Meeting (1884) of the British Association for Advancement of Science.

thermodynamics. The first and second of these divisions are treated of in works on thermodynamics, and in treatises on physics. The third division is briefly considered, and usually very incompletely, in treatises on the steam-engine; while the last is of too recent development to be the subject of complete treatment, as yet, in any existing works. The principal object of the present sketch is simply to collect into a condensed form, and in proper relations, these several branches of the subject, leaving for another time and place that more full and complete account which might, did opportunity offer, be prepared to-day.

The "Mechanical Theory of Heat," as is now well understood, existed, as a speculation, from the days of the earliest philosophies. The contest which raged with such intensity, and sometimes acrimony, among speculative men of science, during the last century, was merely a repetition of struggles of which we find evidences, at intervals, throughout the whole period of recorded history. The closing period of this, which proved to be an important revolution in science, marked the beginning of the nineteenth century. It was inaugurated by the introduction of experimental investigation directed

toward the crucial point of the question at issue. It terminated, about the middle of the century, with the acceptance of the general results of such experiment by every scientific man of acknowledged standing, on either side the Atlantic. The doctrine that heat was material, and its transfer a real movement of substance from the source to the receiver of heat, was thus finally completely superseded by the theory, now become an ascertained truth, that heat is a form of energy, and its transformation a change in the location and method of molecular vibration. The Dynamical Theory of Heat was first given a solid basis by the experiments of Count Rumford (Benjamin Thomson), in 1796–7—of which an account was given in a paper read by Rumford before the Royal Society of Great Britain in 1798—by the experiments of Sir Humphry Davy in 1798–9, and by the later and more precise determinations of the value of the mechanical equivalent of heat, by Joule, in 1843, and subsequently more exactly by Rowland.

The Science of Thermodynamics has for its essential basis the established fact of the dynamical nature of heat, and the fact of the quantivalence of two forms of energy—heat and mechanical

motion, molecular energy and mass energy. Resting, as it does, on fundamental, experimentally determined, principles, it could have no existence until, during the early part of the present century, these phenomena and these truths were well investigated and firmly established. Immediately upon the settlement of the controversy relating to the nature of heat, it became possible to commence the construction of the science which, asserting the mechanical theory of heat as its fundamental fact, and the conservation and quantivalence of the two forms of energy as its fundamental principle, led to the determination of the method and extent of the transformation of the one into the other, during any prescribed series of physical changes.

It is not within the province of this chapter to examine the claims made for rival philosophers, in the debate over the matter of priority of discovery of the mutual relations of the phenomena and principles of the new science. It is sufficiently evident that the revelation of the facts of the case led many minds to study the subject, and led to its nearly contemporaneous development in several countries. The first period of the

development of the science was occupied almost exclusively by the exposition of the dynamical theory of heat, which lies at the bottom of the whole. This strikingly interesting and obviously important subject so absorbed the attention and occupied the thoughts of physicists that they seem hardly to have attempted to look beyond it, as a rule, and hence failed, at first, to see into what a magnificent department of theoretical and experimental investigation they were called. Mohr, in 1837; Seguin, in 1839; Mayer, of Heilbronn, in 1842, and Colding, in 1843, each took a step into a field the limits of which and the importance of which they could at that time hardly have imagined. Mayer certainly had a very clear conception of the bearing of the new theory of heat upon dynamics, and exhibited remarkable insight into the far-reaching principles of the new science. He collated the facts more exactly determined later by Joule and Rowland with the principle of the conservation of energy, and applied the rudiments of a science thus constructed to the calculation of the quantity of carbon and expendiutre of heat which are unavoidably needed by a mountain-climber, doing a given quantity of work, in the

elevation of his own body to a specified height. The work of Mayer may be taken as representing the first step in the production of a Science of Thermodynamics, and in the deduction of the consequences of the fact which had, until his time, so seldom engaged the attention of men of science. It was only about the middle of the century that it began to be plainly seen that there existed such a science, and that the dynamic equivalence of heat, and energy in the mechanical form, was but a single fact, which must be taken in connection with the general principles of the persistence of energy, and applied in all cases of performance of work by expenditure of heat through the action of elastic bodies.

The development of the Science of Thermodynamics into available and satisfactory form was effected mainly by Professors Rankine and Clausius, working independently but contemporaneously from 1847. Clausius developed the general theory with beautiful clearness and conciseness of methematical method and work, and succeeded in constructing a complete system, almost equal in extent and exactness to the geometrical system of Euclid. Rankine, producing the same results, in

part, by his wonderfully condensed method of treatment, turned his attention more closely to the application of the theory to the case of the steam and other heat engines, giving, finally, in his "Prime Movers" (1859), a concise yet full exposition of the correct theory of those motors, so far as it is possible to do so by purely thermodynamic treatment. He was unaware, apparently, as were all the scientific men of his time, of the extent to which the conclusions reached by such treatment of the case are modified, in real engines, by the interference of other physical principles than those taken cognizance of by his science. Sir William Thomson, partly independently, and partly working with Joule, has added much valuable work to that done by Clausius and Rankine. In the hands of these great men the science took form, and has now assumed its place among the most important of all branches of physical science.

The Theory of the Steam-engine, like every other scientific system, rests upon a foundation of facts ascertained by experiment, and of principles determined by the careful study of the laws relating to those facts, and controlling phenomena, properly classed together by that science. Like

every other element entering into the composition of a scientific system, this theory has been developed subsequently to the establishment of its fundamental facts, and the history of progress in the art to which it relates shows that the art has led the science from the first. The theory of the steam-engine includes all the phenomena and all the principles involved in the production of power by means of the steam-engine, from the heat-energy derived from the chemical combination of a combustible with the oxygen of the air acting as a supporter of the combustion. The complete theory therefore includes the theory of combustion; the consideration of the methods of development and transfer, and of losses of heat in the steam-boiler; the examination of the methods of transfer of heat-energy from boiler to engine, and of waste of heat in this transfer; and, finally, the development of mechanical energy in the engine, and its application, beyond the engine, to the machinery of transmission, with an investigation of the nature and method of waste in this last transformation. It is, however, only the last of these divisions of the subject that it is here proposed to consider. The remaining portion of this chapter

will be devoted to the tracing of the growth of the theory of the steam-engine, simply as a mechanical instrument for transformation of the one form of energy into the other—of the molecular energy of heat motion, as stored in the vapor of water, into mass-energy, mechanical energy, as applied to the driving of mechanism. The theory thus limited includes a study of the thermodynamic phenomena, as the principal and essential operations involved in the performance of work by the engine; it further includes the consideration of the other physical processes which attend this main function of the engine, and which, inevitably and unavoidably, so far as is to-day known, concur in the production of a waste of energy.

Of all the heat sent forward by the steam-boiler to the engine, a certain part, definite in amount and easily calculated when the power developed is known, is expended by transformation into mechanical energy; another part, equally definite and easily calculated, also, is expended as the necessarily occurring waste which must take place in all such transformations, at usual temperatures of reception and rejection of heat; still another portion is lost by conduction and radiation to sur-

rounding bodies; and, finally, a part, often very large in comparison with even the first and principal of these qnantities, is wasted by transfer, within the engine, from the induction to the eduction side, "from steam to exhaust," by a singular and interesting process, without conversion into useful effect. The science of thermodynamics only takes cognizance of the first, which is some times one of the smallest of these expenditures. The science of the general physics of heat takes cognizance of the others.

The Science of the Phenomena of the Steam-engine must, like every other branch of applied science, be considered as the product of two distinct processes of development; the one is what may be called the experimental development of the subject, the other is the purely theoretical progress of the science. So far as the useful application of principles to the perfection of the machine is concerned, the latter has always, as is usually the case elsewhere, been in advance of the former in its deduction of general principles; while, as invariably, the former has kept far in advance, in the working out of practically useful results, and in the determination of the exact facts where ques-

tions of economic importance have arisen. It is proposed here to follow the history of the experimental development of the principles controlling the efficiency of the engine, and modifying the conclusions derived by the application of the science of heat-transformation, after first tracing the progress of the development of that science. The gradual formation of the pure theory of the steam-engine will be traced, and the limitations of that theory will naturally come up for consideration afterward.

The germ of a Science of the Steam-engine may be found in the work of Sadi Carnot, published in 1824. Although familiar with the then doubted mechanical theory of heat, he was not sufficiently well convinced of its correctness, apparently, to make it the basis of his work, but assumed, throughout his "*Reflexions sur la Puissance Motrice du Feu,*" the theory of substantial caloric. Nevertheless, in his development of the theory of heat-engines, he ennunciated some essential principles, and thus laid the foundation for a theory of the steam-engine which was given correct form, in all its details, as soon as the dynamical theory was taken for its foundation-principle. Carnot

asserts that "The motive power of heat is independent of the means taken to develop it; its amount is determined, simply, by the temperature of the bodies between which the heat is transferred. Wherever there exists a difference of temperature, there may be a development of power. The maximum amount of power obtainable by the use of steam is the maximum obtainable by any means whatever. High-pressure engines derive their advantage over low-pressure engines simply from their power of making useful a greater range of temperature." He made use of the device known as the "Carnot Cycle," exhibiting the successive expansions and compressions of the working fluid in heat-engines, in the process of change of volume and temperature, while following the series of changes which gives the means of transformation of heat into power with final restoration of the fluid to its initial condition, showing that such a complete cycle must be traversed in order to determine what proportion of the heat-energy available can be utilized by conversion into mechanical energy. This is one of the most essential of all the principles comprehended in the modern

science. This "Carnot Cycle" was, afterward, represented graphically by Clapeyron.

Carnot shows that the maximum possible efficiency of fluid is attained, in heat-engines, by expanding the working fluid from the maximum attainable temperature and pressure down to the minimum temperature and pressure that can be permanently maintained on the side of condensation or rejection, *i. e.*, if we assume expansion according to the hyperbolic law, by adopting, as the ratio of expansion, the quotient of maximum pressure divided by back pressure. He further shows that the expansion, to give maximum efficiency, should be perfectly adiabatic. These principles have been recognized as correct by all authorities, from the time of Carnot to the present time, and have been, not infrequently, brought forward as new by minor later writers unfamiliar with the literature of the subject. Introducing into the work of Carnot the dynamical relation of heat and work, a relation, as shown by other writings, well understood, if not advocated publicly by him, the theory of the steam-engine becomes well defined and substantially accurate. The Comte de Pambour, writing in 1835, and later,

takes up the problem of maximum efficiency of the steam-engine, shows the distinction to be drawn between the efficiency of fluid and efficiency of machine, and determines the value of the ratio of expansion for maximum efficiency of engine. He makes this ratio equal to the quotient of maximum initial pressure divided by the sum of the useless internal resistances of the engine, including back pressure and friction, and reduced to equivalent pressure per unit of area of piston. This result has been generally accepted, although sometimes questioned, and has been demonstrated anew, in apparent ignorance of the fact of its prior publication by De Pambour, by more than one later writer. De Pambour, applying his methods to the locomotive particularly, solved the problem, since distinctively known by his name: Given the quantity of steam furnished by the boiler in the unit of time, and the measure of resistance to the motion of the engine; to determine the speed attainable.

Professor Thomas Tate, writing his "Mechanical Philosophy," in 1853, gives the principle stated above a broader enunciation, thus: "The pressure of the steam, at the end of the stroke, is equal to

the sum of the resistances of the unloaded engine, whatever may be the law expressing the relation of volume and pressure of steam."

Professor Clausius, as has been already stated, applied the modern theory of the steam-engine to the solution of the various problems which arise in the practice of the engineer, so far as they can be solved by the principles of thermodynamics. His papers on this subject were printed in 1856. The Comte de Pambour had taken a purely mechanical mode of treatment, basing his calculations of the work done in the cylinder of the steam-engine upon the hypothesis of Watt, that the weight of steam acting in the engine remained constant during expansion, and that the same assumption was applicable to the expanding mass contained in engine and boiler during the period of admission. He had constructed empirical formulas, published in his work on the theory of the steam-engine, in 1844, for the relation of volume and pressure, during expansion, and had based his determinations of the quantity of work done, and of expenditure of steam in the engine, upon this set of assumptions and formulas, considering the steam to remain in its initial condition of dry and sat-

urated vapor, or of moist vapor, as the case may be, from the beginning to the end of the stroke. Errors were thus introduced, which, although not important in comparison with those often occurring when the results of purely thermodynamic, and in so far correct, treatment was compared with the actual case, were, nevertheless, sufficiently great to become noticeable when the true theory of heat-engines became known, and correctly applied. Clausius proved that, in the expansion of dry and saturated steam, doing work in the engine, condensation must take place to a certain extent, and that, consequently, the weight of steam in the cylinder must be somewhat reduced by the process of expansion beyond the point of "cut-off." During the period of compression, also, the reverse effect must occur, and the compressed mass must become superheated, if initially dry. He showed that the amount of work actually done in a non-conducting working cylinder must be sensibly different from that estimated by the method of De Pambour. Taking advantage of the redetermination of the constants in Regnault's equations effected by Moritz, Clausius obtains numerical results in the application of the true

theory, and deduces the amount of work done in the steam-engine under various conditions such as are met with in practice. He shows how the action of the engine may be made that of the Carnot Cycle, and determines the effect of variation of the temperature of the "prime" steam. The investigation is, in the main, purely theoretical; no application is made to the cases met with in real work, and the comparison of the results of the application of the new theory to practice in steam engineering is left for others.

The work of Clausius is, throughout, perfectly logical, and beautifully simple and concise, and his application of the theory to the steam-engine amounts to a complete reconstruction of the work of Carnot, and his followers, upon a correct basis. He develops with mathematical exactness of method and work the fundamental principles of the science of thermodynamics, constructs the "fundamental equations," the so-called "General Equations of Thermodynamics," and, in the course of his work, proves the fact of the partial condensation of saturated steam, when permitted to expand doing work against resistance.

Professor Rankine began his work upon the

theory of the transformation of heat into mechanical energy at about the same time with Clausius (1847–9), and published his first important deduction, the form of the General Equation of Thermodynamics, nearly simultaneously, but a little earlier. He gave much attention to the then incomplete work of development of applied thermodynamics, and produced not only the whole theory of the science, but very extended papers, including solutions of practical problems in the application of the science to heat-engines. Stating with singular brevity and clearness the main principles, and developing the general equations in substantially the same form, but by less easily followed processes than his contemporary, he proceeded at once to their application. He determines the thermodynamic functions for air and other gases, exhibits the theory of the hot-air engine, as applied to the more important and typical forms, deduces expressions for their efficiency, and estimates the amount of heat demanded, and of fuel consumed, in their operation, assuming no other expenditure of heat than that required in an engine free from losses by conduction and radiation. He next, in a similar manner, applies the theory

to the steam-engine, proves the fact of the condensation of steam during the period of expansion, estimates the amount of heat, fuel, and steam expended, and the quantity of work done, and determines thus the thermodynamic efficiency of the engine. He makes a special case of the engine using superheated steam, as well as that of the "jacketed" engine, considers the superheated steam-engine, and the binary-vapor-engine, and reconstructs De Pambour's problem. Applying the theory of the steam-engine to a considerable number of cases, differing in the steam-pressure and in the ratio of expansion adopted, and including both condensing and non-condensing engines, he constructs a table exhibiting the efficiency of the steam, and the probable consumption of fuel (assuming a somewhat low efficiency of boiler), which table represents the limit of efficiency under the assumed conditions, a limit which may be approached as the conditions of practice approximate to those of the ideal cases taken, but which can never be reached.

As Rankine was not aware of the often enormous differences produced in the performance of the steam-engine by the extra-thermodynamic

phenomena involved in its operation, he does not indicate the fact that the results of his calculations must be taken with the qualification just stated above, and his figures are still sometimes supposed to represent those of actual performance. The fact is, however, that the consumption of steam, and of fuel, in actual practice, always considerably exceeds those obtained by the solution of the thermodynamic problem, and, often, as already stated, exceeds that quantity by a very large amount.

Since the time of Rankine's and Clausius' investigations, the thermodynamic theory of the steam-engine has received no important modifications, and the work of later engineers, and of physicists working upon the general subject, has been confined to the study, experimental or other, of the limitations set to the application of this theory by the influence of other physical phenomena.

Rankine's work included the construction of a remarkably exact, though hypothetical, equation expressing the relation of temperatures and pressures of vapors, based upon his theory of "molecular vortices," a comparison of the efficiencies of air and steam-engines working between the same

limits of temperature, and an exceedingly beautiful method of graphically determining the most economical size of steam-engine, from the commercial point of view, the quantity of power required being given, and all expenses being calculable. He defined and outlined the science of "energetics," established the beginnings of a system of graphical thermodynamics, including the representation of the action of steam in the compound engine. He studied the action of explosive gas-engines, and calculated the explosive energy of liquids heated under pressure. Besides all this, Rankine performed an enormous amount of work in mathematical physics, in hydrodynamics, in hydromechanics, in the theory of naval architecture, and in the application of mechanics to general engineering. Several important text-books, a large volume on shipbuilding, and other works, with an unknown number of papers, published and unpublished, form a monument to the power and industry of this wonderful man and remarkable genius, that may be looked upon as perhaps the greatest wonder of the intellectual world.

The Thermodynamic Theory of the Steam-engine stands, to-day, substantially as it was left by

Clausius and Rankine at the close of their work in this field, in the decade 1850 to 1860. Many treatises have been published, some of them by men of exceptional ability; but all have followed the general line first drawn by these masters, and have only now and then found some minor point to develop. Rankine's "Steam Engine and other Prime Movers," written in 1857–9, is still a standard work on the theory of the heat-engines, and is still used as a text-book in engineering-schools in this country and Europe.

The Limitations of the Thermodynamic Theory of the Heat-engines, and of its application in the design and operation of such engines, were first discovered by James Watt, a hundred years ago and more. They were observed and correctly interpreted by Clark, in 1885 and earlier, were systematically and experimentally investigated by Isherwood, in 1855 to 1865, and were revealed again by the experiments of Hirn, and by those of Emery and many other recent investigators on both sides of the Atlantic. These limitations are due to the fact that losses occur, in the operation of steam-engines, which are not taken into account by the hitherto accepted theory of the engine, and

have no place in the thermodynamic treatment of the case.

It is commonly assumed, in the usual theory of the unjacketted engine, that the expansion of the working-fluid takes place in a cylinder having walls impermeable to heat, and in which no losses by conduction or radiation, or by leakage, can occur. Of those losses which actually take place in the real engine, that due to leakage may be prevented, or, if occurring, can be checked; but it is impossible, so far as is now known, to secure a working-cylinder of perfectly non-conducting material. The consequence is that, since the steam or other working-fluid enters at a high temperature and is discharged at a comparatively low temperature, the surfaces of cylinder, cylinder-heads and piston, are, at one instant, charged with heat of high temperature, and at the next moment exposed to lower temperatures, are drained of their surplus heat, which heat is then rejected from the cylinder and wasted. Thus, at each stroke, the metal surfaces, exposed to the action of the expanding substance, alternately absorb heat from it, and surrender that heat to the "exhaust." In the case of the gas-engines, this waste is rendered

enormously greater by the action of the water-jacket, which is there needed to keep the cylinder down to a safe temperature, and which takes away, in the circulating stream of cooling water, an immense amount—usually about one half—of the heat received from the burning gas. In the steam-engine the loss by the method here referred to is rarely less than one fourth in unjacketted cylinders, and is often more than equal to the whole quantity of heat transformed into mechanical energy. The amount of this loss increases with wet steam and is diminished by any expedient, as steam-jacketting or superheating, which prevents the introduction or the production of moisture in the midst of the mass of steam in the cylinder. As the range of temperature worked through in the engine increases as the quantity of steam worked per stroke diminishes, and as the time allowed for transfer of heat to and from the sides and ends of the cylinder and the piston is increased, the magnitude of this loss increases. Hence the use of high steam, of a high ratio of expansion, and of low piston-speed, tends to increase the amount of this waste, while low steam, a low ratio of expansion, and high engine-speed tend to diminish it.

These physical phenomena are therefore no less important in their influence upon the behavior of the engine, and upon its efficiency, and are no less essential elements for consideration in the general theory of the engine, than those taken into account in the purely thermodynamic theory.

James Watt, as above stated, discovered this cause of the limitation of the efficiency of the steam-engine. He not only discovered the fact of the existence of this method of waste, but experimentally determined its amount in the first engine ever placed in his hands. It was in 1763 that he was called upon to repair the little model of the Newcomen engine, then and still in the cabinets of the University of Glasgow. Making a new boiler, he set up the machine and began his experiments. He found, to his surprise, that the little steam-cylinder demanded four times its own volume, at every stroke, thus wasting, as he says, three fourths of the steam supplied, and requiring much more as "injection-water" than should suffice to condense a cylinderful of steam. It was in the course of this investigation that he discovered the existence of so-called "latent heat." All of Watt's first inventions were directed toward the reduc-

tion of this immense waste. He proposed to himself the problem of keeping the cylinder "as hot as the steam that entered it;" he solved this problem by the invention of the separate condenser and the "steam-jacket," and thus the discovery of the limitation of the thermodynamic theory here noted was the source of Watt's fame and fortune.

John Smeaton, a distinguished contemporary of Watt, and perhaps the most distinguished engineer of his time, seems to have been not only well aware of this defect of the steam-engine, but was even in advance of Watt in attempting to remedy it. He built a large number of Newcomen engines between 1765 and 1770, in some if not many of which he attempted to check loss by this now familiar "cylinder condensation" in engines, some of which were five and six feet in diameter of cylinder, by lining pistons and heads with wood. This may not be practicable with the temperatures now usual; but no attempt has been made, except by Emery, so far as is known to the Author, to follow Smeaton in his thoroughly philosophical plan of improvement. Cylinder-condensation remains to-day, as in the time of Smeaton and Watt,

the chief source of possibly avoidable waste in all well-designed and well-constructed heat-engines.

It is a curious fact, and one of great interest as illustrating the gulf separating the philosopher, studying the steam-engine and working out its theory, from the practitioner engaged in its construction and operation, in the earlier days of engineering, that, notwithstanding the fact that this waste was familiar to all intelligent engineers, from the time of the invention of the modern steam-engine, and was recorded in all treatises on engine construction and management, the writers on the theory of the machine have apparently never been aware that it gives rise to the production, in the working cylinder, of a large amount of water mingled with the steam. In fact it has often been assumed by engineers themselves, that this water is always due to "priming" at the boiler. Even Rankine, writing in 1849–50, while correctly describing the phenomenon of cylinder-condensation, made the mistake of attributing the presence of the water in steam-cylinders to the fact of condensation of dry steam doing work by expansion, apparently not having noted the fact that this would only account for a very insignificant proportion of

the moisture actually present in the average steam-engine. He considers incomplete expansion the principal source of loss, as do usually other writers on thermodynamics.

Thomas Tredgold, writing in 1827, who, but little later than Carnot, puts the limit to economical expansion at the point subsequently indicated and more fully demonstrated by De Pambour, exaggerates the losses due to the practical conditions, but evidently does perceive their nature and general effect. He also shows that, under the conditions assumed, the losses may be reduced to a minimum, so far as being dependent upon the form of the cylinder, by making the stroke twice the diameter.

The limit of efficiency in heat-engines, as has been seen, is thermodynamically determined by the limit of complete expansion. So well is this understood, and so generally is this assumed to represent the practical limit, by writers unfamiliar with the operation of the steam-engine, that every treatise on the subject is largely devoted to the examination of the amount of the loss due to what is always known as "incomplete expansion"—expansion terminating at a pressure higher than

the back-pressure in the cylinder. The causes of the practical limitation of the ratio of expansion to a very much lower value than those which maximum efficiency of fluid would seem to demand, have not been usually considered, either with care or with intelligence, by writers thoroughly familiar with the dynamical treatment apart from the modifying conditions here under consideration.

Watt, and probably his contemporaries and successors, for many years supposed that the irregularity of motion due to the variable pressure occurring with high expansion was the limiting condition, and does not at first seem to have realized that the cylinder-condensation discovered by him had any economical bearing upon the ratio of expansion at maximum efficiency. It undoubtedly is the fact that this irregularity was the first limiting condition with the large, cumbrous, long-stroked, and slow-moving engines of his time. Every accepted authority from that day to the present has assumed, tacitly, that this method of waste has no influence upon the value of that ratio, if we except one or two writers who were practitioners rather than scientific authorities.

The direction in which further improvement

must take place in the standard type of engine is plainly that which shall most efficiently check losses by internal condensation and re-evaporation by the transfer of heat to and from the metal of the steam-cylinder. The condensation of steam doing work is evidently not a disadvantage, but, on the contrary, a decided advantage.

To secure this vitally important economy, it is advisable to seek some practicable method of lining the cylinder with a non-conducting material.* The loss will also be reduced by increasing the speed of rotation and velocity of piston. Where no effectual means can be found of preventing contact of the steam with a good absorbent and conductor of heat, it will be found best to sacrifice some of the efficiency due to the change of state of the vapor, by superheating it and sending it into the cylinder at a temperature considerably

* This plan was adopted by Smeaton, in constructing Newcomen engines a century ago. Smeaton used wood on his pistons. Watt tried wood as a material for steam-cylinder-linings. That material is too perishable at temperatures now common, and no metal has yet been substituted, or even discovered, which answers the same purpose.

exceeding that of saturation. With low steam and slowly moving pistons, it is better to pursue the latter course than to attempt to increase the efficiency of the engine by greater expansion.

Increasing steam-pressure and expanding to a greater extent will give theoretically slightly increased economy. Repeating the calculation made above, using as constants the temperature, volumes and pressures of steam entering the cylinder at 250 pounds, and expanding down to the same point, it will be found that the gain in efficiency is but a few per cent. It is not in that direction, therefore, that we are to expect great improvement.

Mr. D. K. Clark, publishing his "Railway Machinery," in 1855, was the first to discuss this subject with knowledge, and with a clear understanding of the effects of condensation in the cylinder of the steam-engine, upon its maximum efficiency. Cornish engines, from the beginning, had been restricted in their ratio of expansion to about one fourth, as a maximum, Watt himself adopting a "cut-off" at from one half to two thirds. Hornblower, with his compound engine competing with the single-cylinder engines of

Watt, had struck upon this rock, and had been beaten in economy by the latter, although using much greater ratios of expansion; but Clark, a half-century and more later, was nevertheless the first to perceive precisely where the obstacle lay, and to state explicitly that the fact that increasing expansion leads to increasing losses by cylinder-condensation, the losses increasing in a much higher ratio than the gain, is the practical obstruction in our progress toward greater economy.

Clark, after a long and arduous series of trials of locomotive engines, and prolonged experiment looking to the measurement of the magnitude of the waste produced as above described, concludes: "The magnitude of the loss is so great as to defeat all such attempts at economy of fuel and steam by expansive working, and it affords a sufficient explanation of the fact, in engineering practice, that expansive working has been found to be expensive working, and that in many cases an absolutely greater quantity of fuel has been consumed in extended expansion working, while less power has been developed." He states that high speed reduces the effect of this cause of loss, and indicates

other methods of checking it. He states that "the less the period of admission relative to the whole stroke, the greater the quantity of free water existing in the cylinder." His experiments revealing these facts were in some cases made prior to 1852. But the men handling the engines had observed this effect even before Clark; he states that they rarely voluntarily adopted "a suppression of above 30 per cent," as they found the loss by condensation greater than the gain by expansion. Describing the method of this loss, this author goes on to say that "to prevent entirely the condensation of steam worked expansively, the cylinder must not only be simply protected by a non-conductor; it must be maintained, by independent external means, at the initial temperature of the steam." He thus reiterates the principle expressed by Watt three quarters of a century before, and applies it to the newly stated case.

The same author, writing in 1877, says: "The only obstacle to the working of steam advantageously to a high degree of expansion in one cylinder, in general practice, is the condensation to which it is subjected, when it is admitted into the cylinder at the beginning of the stroke, by the

less hot surfaces of the cylinder and piston; the proportion of which is increased so that the economy of steam by expansive working ceases to increase when the period of admission is reduced down to a certain fraction of the stroke, and that, on the contrary, the efficiency of the steam is diminished as the period of admission is reduced below that fraction." The magnitude of this influence may be understood from the fact that the distinguished engineer Loftus Perkins, using steam of 300 pounds pressure, and attaining the highest economy known up to his time, found his engine to consume 1.62 pounds of fuel per hour and per horse-power; while this figure is now reached by engines using steam at less than one third that pressure, and expanding about the same amount, and sometimes less.

Mr. Humphreys, writing a little later than Clark, shows the consumption of fuel to increase seriously as the ratio of expansion is increased beyond the very low figure which constituted the limit in marine engines of his time.

Mr. B. F. Isherwood, a chief engineer in the United States Navy, and later Chief of the Bureau of Steam Engineering, seems to have been the first

to have attempted to determine, by systematic experiment, the law of variation of the amount of cylinder-condensation with variation of the ratio of expansion, in unjacketed cylinders. Experimenting on board the U. S. S. *Michigan,* he found that the consumption of fuel and of steam per horse-power and per hour was greater when the expansion was carried beyond about one half-stroke than when restricted to lower ratios. He determined the quantity of steam used, and the amount condensed, at expansions ranging from full stroke to a cut-off at one tenth. His results permit the determination of the method of variation, with practically satisfactory accuracy, for the engine upon which the investigation was made, and for others of its class. It was the first of a number of such investigations made by the same hand, and these to-day constitute the principal part of our data in this direction. The author, studying these results, found that the cylinder-condensation varied sensibly as the square root of the ratio of expansion; and this is apparently true for other forms and proportions of engine. The amount of such condensation usually lies between one tenth and one fifth the square root of that ratio, if estimated

as a fraction of the quantity of steam demanded by a similar engine having a non-conducting cylinder.

The state of the prevalent opinion on this subject, at the time of this work of Clark and of Isherwood, is well expressed by the distinguished German engineer Dr. Albans, who, writing about 1840, says of the choice of best ratio of expansion: "Practical considerations form the best guide, and these are often left entirely out of view by mathematicians. Many theoretical calculations have been made to determine the point, but they appear contradictory and unsatisfactory." Renwick, in 1848, makes the ratio of initial divided by back pressure the proper ratio of expansion, but correctly describes the effect of the steam-jacket, and suggests that it may have peculiar value in expansive working, and that the steam may receive heat from a cylinder thus kept at the temperature of the "prime" steam. John Bourne, the earliest of now acknowledged authorities on the management and construction of the steam-engine, pointed out, at a very early date, the fact of a restricted economic expansion. Rankine recognized no such restriction as is here under consideration, and con-

sidered the ratio of expansion at maximum efficiency to be the same as that stated by Carnot, and by other early writers, and only perceived its limitation by commercial considerations,—a method of limitation of great importance, but often of less practical effect than is the waste of condensation. In his life of Elder (1871), however, he indicates the existence of a limit in practice, and places the figure at that previously given by Isherwood, for unjacketed engines. By this latter date, the subject had become so familiar to engineers that a writer in *London Engineering,* in 1874, contemns writers who had neglected to observe this limitation of efficiency as indulging in "mediæval twaddle."

A few writers on thermodynamics finally came to understand the fact that such a limitation of applied theory existed. Mons. G. A. Hirn, who, better than probably any authority of his time or earlier, combined a knowledge of the scientific principles involved, with practical experience and experimental knowledge, in his treatise on thermodynamics (1876), concludes: "*qu'il est absolument impossible d'édifier* a priori *une théorie de la machine à vapeur d'eau douce d'un charactère*

scientifique et exact," in consequence of the operation of the causes here detailed. Mons. Combes, as early as 1867, calls attention to this waste.* He suggests that the utility of the steam-jackets may lie in its reduction of internal condensation. Verdet (1868) recognizes the existence of cylinder-condensation.† He perceived the effect of wet steam in exaggerating that waste. Probably the first attempt to give a mathematical theory was made by Woirhays in 1873;‡ but Mons. Hirn has paid more attention to the subject, especially in experimental investigation, than any other writer of his time. While working up his experiments upon the performance of engines, comparing the volume of steam used with that of the cylinder, he had always found a great excess, and had at first attributed it to the leakage of steam past the piston; but a suggestion of Mons. Leloutre set him upon the right track, and he came to the same conclusion as had Watt so many years before. He explains that errors of thirty or even up to seventy per

* Theorie mechanique de la Chaleur, Paris, 1867.

† Theorie de la Chaleur, Paris, 1868.

‡ Essai sur la rendement calorifique des machines à vapeur.

cent may rise from the neglect of the consideration of this loss. Combes had perceived the importance of this matter, and De Freminville suggested the now familiar expedient of compression, on the return stroke, as nearly as possible to boiler-pressure, as a good way to correct the evil. The matter is now well understood by contemporary writers, and it has become fully agreed, among theoretical writers as well as among practitioners, that the benefit of extended expansion in real engines can only be approximated to that predicted by the theory of the ideal engine, by special arrangements having for their object the reduction of cylinder-waste, such as superheating, "steam-jacketing," and "compounding."

Professor Cotterill has given more attention to this subject than any writer up to the present time. He devotes a considerable amount of space to the study of the method of absorption and surrender of heat by the metal surfaces inclosing the steam, constructs diagrams which beautifully illustrate this action, and solves the problems studied by him with equal precision and elegance of method. He summarizes the experimental work done to the date of writing, and very fully and clearly exhibits

the mode of transfer of heat past the piston without transformation into work.

Thus the theory of the steam-engine stands to-day, incomplete, but apparently on the verge of completion, needing only a little well-directed experimental work to supply the doubtful elements. Even these are becoming determined. Isherwood gives facts showing waste to be proportional, very nearly, if not exactly, to the square root of the ratio of expansion, and Escher, of Zurich, has shown the loss to be also proportional to the square root of the time of exposure, or, in other words, to the reciprocal of the square root of the speed of rotation; and it only remains to determine the method of variation of loss with variation of range of temperature to give the whole of the necessary material for the construction of a working theory which will enable the engineer to estimate, in advance of construction, the economic performance of his machine. There will undoubtedly be much more to be done in constructing an exact theory involving all the physical changes occurring in the working of the heat-engines familiar to us; but it will yet be done, and probably very soon. It cannot be long before direct investigation will secure

all essential knowledge. When this is the case the remarks of those distinguished physicists and engineers, Hallauer, and his great teacher, Hirn, will be no longer well based upon apparent fact.

Says Hirn, in his memorable discussion with Zeuner, in regard to this subject: "*Ma conviction reste aujourd'hui qu'elle etait il y a vingt ans, une théorie proprement dite de la machine à vapeur est impossible; la théorie experimentale, etablie sur le moteur luimeme et dans toutes les formes ou il a été essayé, en mecanique appliqué peut seule conduire a des resultats rigoureux.*"

At present, it seems only possible, in the absence of a complete experimental examination, to do more than to base the determination of the ratio of maximum efficiency upon such experience as is familiar to engineers. Mr. C. E. Emery considers that, for common unjacketed engines, it is practically safe to take the ratio for maximum duty at a figure expressed by an empirical formula proposed by him: $r = (p + 37) \div 22$. The Author has usually taken it, in estimates, as not far from one half the square root of the boiler-pressure expressed, as before, in pounds on the square inch. These points of cut-off are reduced still further

by the fact that, commercially, it is better to reduce the size of engine at the expense of efficiency as the cost of fuel and of similarly variable expenses increase. The subject will form, properly, a final division of the complete theory of the steam-engine.

Chronologically considered it is seen that the history of the growth of the theory of the steam-engine divides itself distinctly into three periods,—the first extending up to the middle of the present century, and mainly distinguished by the attempts of Carnot and of Clapeyron to formulate a physical theory of the thermodynamics of the machine; the second beginning with the date of the work of Rankine and Clausius, who constructed a correct thermodynamic theory; and the third beginning a generation later, and marked by the introduction, into the general theory, of the physics of the conduction and transfer of that heat which plays no part in the useful transformation of energy. The first period may be said to include also the inauguration of experimental investigation, and the discovery of the nature and extent of avoidable wastes and attempts at their amelioration by James Watt and by John Smeaton. The second period

is marked by the attempt, on the part of a number of engineers, to determine the method and magnitude of these wastes by more thorough and systematic investigation, and the exact enunciation of the law governing the necessary rejection of heat, as revealed by the science of thermodynamics. The third period is opening with promise of a complete and practically applicable investigation of all the methods of loss of energy in the engine, and of the determination, by both theoretical and experimental research, of all the data needed for the construction of a working theory.

Mons. Hirn has recognized these three periods, and has proposed to call the second the "theoretical" and the third the "experimental" stage. The Author would prefer to make the nomenclature somewhat more accordant with what has seemed to him to be the true method of development of the subject. It has been seen that the experimental stage really began with the investigations of Watt in the first period, and that the work of experimentation was continued through the second into the present, the last, period.

It is also evident that the theoretical stage, if it can be properly said that such a period may be

marked off in the history of the theory of the steam-engine, actually extends into the present epoch; since the work of the engineer and the physicist of to-day consists in the application of the science of heat-transfer and heat-transformation together, to the engine. During the second period, the theory included only the thermodynamics of the engine; while the third period is about to incorporate the theory of conduction and radiation into the general theory with the already established theory of heat-transformation. The Author would therefore make the classification of these successive stages in the progress here described thus:

(1) Primary Period.—That of incomplete investigation and of earliest systematie but inaccurate theory.

(2) Secondary Period.—That of the establishment of a correct thermodynamic theory, the *Theory of the Ideal Engine.*

(3) Tertiary Period.—That of the production of the complete theory of the engine, of the true *Theory of the Real Engine.*

The work of developing this theory is still incomplete. It remains to be determined, by ex-

periment, precisely what are the laws of transfer of heat between metal and vapor, in the engine cylinder, and to apply these laws in the theory of the machine.

A real beginning has, however, been made in this final research. The work of Clark was a qualitative investigation which the later researches of Hirn and of Isherwood supplemented by their quantitative measures of internal wastes. The first systematic investigation of the methods of variation of these wastes with variation of the principal quantities determining their magnitudes was made in 1884 by Messrs. Gately and Kletsch, at Sandy Hook, Connecticut, under the direction and supervision of the Author, and following a plan some years previously schemed out by him.* The general results of this investigation supply the needed data for a complete provisional theory of the steam-engine, including the physical as well as the thermodynamic phenomena, the theory of wastes as well as the theory of heat-trans-

* Journal Franklin Institute, 1885.

formation. It has thus been made possible to construct a theory of the heat-engines which may serve as a guide in design, and in construction, and as a check upon the experimental determinations of efficiency made at test-trials. It has now for the first time become possible to predict on theoretical grounds the performance of any well-constructed steam-engine, and to base upon preliminary computations a very approximate estimate of the probable consumption of steam, heat, and fuel of a steam-apparatus which it may be proposed to design. It is also now practicable to make intelligent and useful estimates of the relative value of alternative plans of construction of proposed new types of engine, and of probable actual costs of operation and of efficiencies, for any given type, size, and design of engine.

The theory of the compound, or the multi-cylinder, engine has now become (1889) well understood and its fundamental principles recognized. These are that the limitations of the efficiency of the single cylinder preclude the adoption of high ratios of expansion, and that the wastes of the multi-cylinder engine are approximately measured by the wastes of that one of its cylinders which is

most subject to loss. The experiments made at Creusot on the single-cylinder Corliss engine, and those of Mr. Willans on his multi-cylinder engines, have afforded the latest and best sets of constants for use in the most accurate of recently constructed theories of the steam-engine.

It was remarked by the Author, in closing a paper presented to the American Society of Mechanical Engineers, April, 1882:

"By the use of this or of some more exact method, the art of proportioning the steam-engine can be elevated to the rank of a branch of the Science of Engineering, and that part of that science which has hitherto been in a most unsatisfactory condition, as viewed from the standpoint of the engineer engaged in its application, may be found to take a comparatively complete and useful form. It is even to be hoped, if not expected, that an exact theory of steam-engine economy may, at some early date, be produced, and that thus the engineer may be enabled to obtain solutions of all such problems with all the precision that can ever be desired."*

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* Efficiencies of the Steam-engine.

This point has apparently to-day been reached, and it only remains for some later Rankine to give the philosophy of the steam-engine its most perfect form by collating and suitably arranging the knowledge and the principles now well established.